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Tri-stress Accelerated Life Test for Cylinders

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Abstract

A life-stress model for cylinders was built based on wear fault mechanism, and the test scheme was optimized using temperature, pressure and velocity as acceleration stresses. An accelerated life test for cylinders was designed and implemented. Life eigenvalues at different stress levels were acquired and analyzed. Undetermined parameters of acceleration model were estimated, and life indices under normal stress condition were extrapolated and compared with those from normal stress test. The feasibility of the optimization scheme and the correctness of the acceleration model were verified. Compared with twin-stress accelerated life test for cylinders, the test period was further shortened.

Keywords:cylinder; accelerated life test; accelerated model; optimism design; weibull distribution

1. Introduction

As the execution element of pneumatic system, cylinder has been widely applied in aeronautics, astronautics, mechanics and other fields, and its service life is one of the important indications. However, if life test at normal stress is conducted with existing method prescribed by the criteria of pneumatic industry, not only the design period is extended, but plenty of labor, material and money will be involved. Therefore, exploration of a feasible accelerated life test method for cylinders is of important significance in both theory and practice.

This study aims at investigating triple-stress accelerated life test methods for cylinders based on existing research work for the development of a feasible optimization scheme. In other words, Stat. precision can be secured, and various life indications under normal stress can be calculated correctly; on the other hand, the test period can be further shortened in comparison with twin-stress accelerated life test, and test cost can be reduced.

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2. Research of cylinder failure mechanism and life-stress model

2.1. Why should the life-stress model for cylinders be built?

Both Arrhenuis model and Eyring model are presently being widely applied. However, the two models are deduced based on the failure mechanism of activation model for electronic products, and the failure mechanism of electronic elements is different from mechanical failure mechanism [1]. These two models are equivalent in both essence and form, and their basic difference is as follows:

Arrhenuis model is an empirical formula obtained from results of failure tests on electronic elements, while Eyring model is a theoretical result from chemistry and quantum mechanics;

Arrhenuis model only describes the relation of failure with temperature, while in Eyring model; it is believed that the correlation of failure and other stress types can also be given in similar mathematical forms [2].

However, stress function S_i in the model does not correspond to universal mathematical expression, and its function variation relation may also change with different failure mechanisms. Besides, there may exist over five undetermined constants in the model, some of which might be merely small second quantities. Therefore, such a model may produce feasibility problem when being applied in practical engineering problems. The other difficulty of Eying model is the measurement units of involved parameters. Users can not determine proper measurement units other than using their experiences [3].

2.2. Condition presumption for accelerated life test

Principle of test condition determination: (1) the product failure mechanism is fixed, and shape parameter β is unchanged for Weibull distribution; (2) a regular acceleration process exists; (3) the life distribution models are identical and regular [4].

2.3. Research on life-stress model

Based on Stribeck-model tribology theory, a life-stress model is obtained through analysis and deduction, as shown in formula (1). The life here can be characteristic life or mean life, etc. Characteristic life is adopted here.

$$ln\eta_{ijlm}=a+\frac{b}{K}+cln(1+V)+d\,lnF_N+eP \qquad (1)$$

Where η_{ijkl} is characteristic lives at different stress levels, with measurement unit of times; T_i is the stress of environmental temperature in cylinder, with K as the unit; V_j is the stress of actuation velocity of piston rod, with m/s as the unit; F_{Nl} is the stress of normal-pressure of piston rod, with N as the unit; P_k is the stress of gas-source supply pressure, with Mpa as the unit; a,b,c,d and e are undetermined coefficients without units, and subscripts i,j,l and m represent stress types; T_0,V_0,F_{N0} and P_0 represent temperature, velocity, normal loading pressure and gas-source supply pressure at normal stress for use.

Formula (1) is a common-sense life-stress model for cylinders.

Let $\varphi_1(S_i)=\frac{1}{T}$, $\varphi_2(S_j)=\ln(1+V)$, $\varphi_3(S_l)=F_N$ and $\varphi_4(S_m)=P$, where S_i,S_j,S_l and S_m represent different stress types, and $\varphi_1,\varphi_2,\varphi_3$ and φ_4 represent known functions corresponding to formula (1). Thus, formula (1) can be expressed as:

$$\ln\eta_{ijlm}=a+b\varphi_1(S_i)+c\varphi_2(S_j)+d\varphi_3(S_l)+e\varphi_4(S_m) \qquad (2)$$

2.4. Research on Acceleration Factor-stress model

Acceleration factor is used to describe the ratio of characteristic life at use stress to that at acceleration stress. It has a number of functions and can be applied for product reliability filtering, product reliability acceptance, comparison of reliability qualities of two products, appraisal of product-quality improvement measures and whole-machine reliability design, etc.

It is expressed by the following formula [5]:

$$A_F = \frac{L_0}{L_{ijlm}} \tag{3}$$

Where A_F is the acceleration factor; L_0 is the life value at use stress (it can be characteristic life or mean life; here characteristic life η_0 is adopted), with cycle as the unit; L_{ijlm} is the life value at acceleration stress (it can be characteristic life or mean life; here characteristic life η_{ijlm} is adopted), with cycle as the unit.

The acceleration factor-stress mathematical model in this test is:

$$A_F = \frac{L_0}{L_{ijlm}} = \frac{e^{abcde\frac{\ln(1+V_0)\ln F_{N0}P_0}{T_0}}}{e^{abcde\frac{\ln(1+V_j)\ln F_{Nl}P_m}{T_i}}} = e^{abcde\left(\frac{\ln(1+V_0)\ln F_{N0}P_0}{T_0} - \frac{\ln(1+V_j)\ln F_{Nl}P_m}{T_i}\right)} \tag{4}$$

Formula (4) is the acceleration factor-stress mathematical model, from which it can be seen that there are five undetermined constants: a, b, c, d and e. Therefore, at least five groups of test data are needed to draw the five-dimensional function curve under the simultaneous effect of four stress quantities in formula (4).

Let's take a look at formula (4): if only curves of temperature and acceleration factor are concerned, the temperature is in continuous changing, and velocity, normal loading pressure and gas-source supply pressure are fixed, then, c, d, e, V_j, F_{Nl} and P_m in formula (4) are some known constants.

In formula (4), if $e^{\left(\frac{\ln(1+V_0)\ln F_{N0}P_0}{T_0}\right)} = \varepsilon_1$, $cde = \varepsilon_2$ and $\ln(1+V_j)\ln F_{Nl}P_m = \varepsilon_3$, then formula (4) is changed into:

$$A_{FT} = e^{ab\varepsilon_2\left(\varepsilon_1 - \frac{\varepsilon_3}{T}\right)} \tag{5}$$

Where A_{FT} is acceleration factor affected solely by temperature, and a and b are undetermined coefficients.

From formula (5), it can be seen that the values of a and b can be determined only with two temperature stress levels and two acceleration factors, and the curve expressed by formula (5) can be determined. Here formula (5) is the expression of acceleration factor-temperature function.

$$A_{FV} = e^{ac\varepsilon_4(\varepsilon_1 - \varepsilon_5\ln(1+V))} \tag{6}$$

The equation for acceleration factor vs. normal loading pressure curve is formula (7):

$$A_{FF_N} = e^{ad\varepsilon_6(\varepsilon_1 - \varepsilon_7\ln F_N)} \tag{7}$$

The equation for acceleration factor vs. gas-source pressure curve is formula (8):

$$A_{FP} = e^{ae\varepsilon_8(\varepsilon_1 - \varepsilon_9 P)} \tag{8}$$

Where A_{FV}, A_{FF_N} and A_{FP} are acceleration factors under the separated influence of velocity, normal loading pressure and gas-source supply pressure, respectively. $\varepsilon_4, \varepsilon_5, \varepsilon_6, \varepsilon_7, \varepsilon_8$ and ε_9 are known constants under given conditions. When initial temperature, velocity, pressure as well as test temperature, pressure and velocity are determined, the values of $\varepsilon_4, \varepsilon_5, \varepsilon_6, \varepsilon_7, \varepsilon_8$ and ε_9 can be determined. In this test, variables for normal use were chosen for test temperature, pressure and velocity.

3. Scheme optimization and design of experiment conditions

3.1. Scheme optimization

Optimization principle: the life quantile of product at normal stress level is $\eta_p(\varphi_0)$, and p is the probability; φ_0 is the stress level in normal use. It is required that the MLE asymptotic variance $Var(\eta_p(\varphi_0))$ of $\eta_p(\varphi_0)$ should be minimized [6]218.

Optimization method: three stress levels are selected: φ_H, φ_M and φ_L, where the highest stress level is fixed and given according to experience or by designers. The middle stress level $\varphi_M = (\varphi_L + \varphi_H)/2$; in the mean time, the proportion of samples at middle stress level φ_M is given generally as: 0.1 or 0.2. The lowest stress level φ_L and its sample proportion π_L are searched, so that the MLE asymptotic variance of parameter $\eta_p(\varphi_0)$ reaches the minimum [6]219.

After optimization design based on the above principle, the velocity stress level and the pressure stress level are chosen, as shown in Table 1. Twenty-six is chosen for the sample capacity.

Table 1. Optimization of accelerated life test for cylinders

stress levels	$V(m/s)$	$P_K(Mpa)$	π_{ik}	Expect failure ratio/ (%)
Normal	0.25	0.5		
lowest	0.19	0.3	0.49	49
middle	0.21	0.5	0.2	20
highest	0.35	0.7	0.31	31

3.2. Construction of references Determination of experiment condition matrix

The matrix is provided by designers of X-series cylinders. The conditions for normal use are: environmental temperature: 308K; velocity: 0.05m/s; pressure: 1.0 MPa. Extreme conditions: temperature: 338K; velocity: 0.6m/s; pressure: 2.5 MPa. Since sixteen tests with temperature and velocity as the acceleration stress have been conducted, only one temperature stress level (338K) was chosen in order to better grasp the influence of pressure and velocity. According to Table 1, the adopted 1.3Mpa,1.9Mp and 2.5Mpa. The adopted velocity stress spectra are: 0.24m/s, 0.37m/s and 0.6m/s. Thus, an experiment condition matrix is obtained, as shown in Table 2.

Table 2. Optimization of accelerated life test for cylinders Stress-spectrum condition matrix at 338K

stress levels	$V(m/s)$		$P_K(Mpa)$	
T/（K）	$V(m/s)$		√	
	0.19		√	
338	0.21	√		√
	0.35	√		√

Symbol '√' in the table represents adopted stress combination. Assuming the total samples is 26, according to Tab1

The samples under(0.37m/s，1.3Mpa)and (0.60m/s，1.3Mpa)is 13, the samples under(0.37m/s，1.9Mpa)and(0.37m/s，2.5Mpa)is 5, the samples under(0.37m/s，2.5Mpa)and(0.60m/s，2.5Mpa)is 8.

4. Estimation and evaluation of parameters in different tests

4.1. Estimation and evaluation of life parameters

According experience, the service life of cylinder follows twin-parameter Weibull distribution[7]. Meso-position ranking method was adopted, the upper single-side confidence-interval was set at 95%. Estimated results of characteristic life, mean life and shape parameter are shown in Table 3.

Table 3 Stat. of characteristic life at different stress levels

Stress composition			η（/s）	M（/s）	β_i
T/(K)	V/(m/s)	P/(Mpa)			
338	0.19	0.13	8271000	7687000	6.20
338	0.21	0.13	6229131	5768200	6.00
338	0.21	0.19	5652000	5253100	6.20
338	0.35	0.19	4708842	4383200	6.28
338	0.35	2.5	4182528	3896600	6.38
338	0.25	0.5	18130000	16780000	6.25

Table 3 shows that the difference of shape parameters at different stress levels: $\Delta = \frac{\beta_{\max} - \beta_{\min}}{\beta_{\min}} = 4.9\%$, which falls into the allowed range, so the presumption of cylinder life following twin-parameter Weibull distribution is correct; the general value of β is solved as 6.25.

Cylinder life decreases with increased pressure and increased actuation speed, with certain regularity, indicating that the selection of stress spectra is correct.

4.2. Estimation and evaluation of acceleration factors

Table 4 Stat. of acceleration factors at different stress levels

Stress composition			*Accelerated*
T(K)	*V(m/s)*	*P(Mpa)*	*Coefficients A_{fv}*
338	0.35	0.7	2.68
338	0.21	0.7	3.56
338	0.21	0.5	3.92
338	0.19	0.5	4.72
338	0.35	0.3	5.21

From Table 4, it can be seen that acceleration factors increa se with increased pressure and increased velocity;

With the data in Table 3 being substituted into formula (6) to solve a and c, the curve of acceleration factor-velocity function (formula (6)) can be determined, as shown in Fig. 1:

With the data in Table 3 being substituted in formula (7) to solve a and d, the acceleration factor-pressure function curve corresponding to formula (7) can be determined, as shown in Fig. 2:

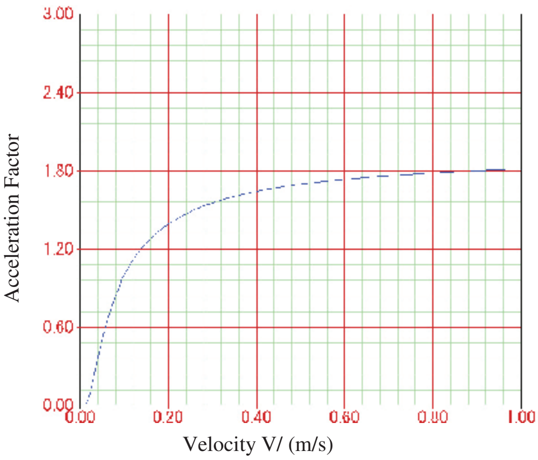


Fig. 1 Curve of acceleration factor vs. velocity

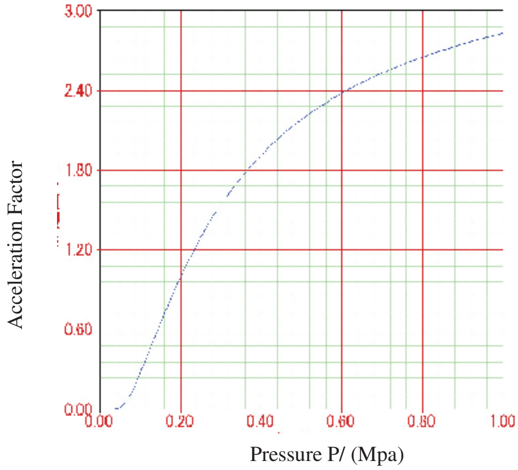


Fig. 2 Curve of acceleration factor vs.
pressure

From Fig. 1 and Fig. 2, it can be seen that compared with pressure, velocity has less influence on cylinder life, so pressure should be the first choice in acceleration stress selection; besides, for the sake of users, adoption of proper using pressure can extend the service life of a cylinder.

5. Parameter estimation and normal-stress life calculation for life-stress model

5.1. Estimation and evaluation of parameters in life-stress model

Mathematical model (1) with velocity and temperature as acceleration stress has been proved as correct in previous sixteen accelerated life tests, and the following results are obtained:

$b = 4546$, $c = -0.73$

This test is still based on mathematical model (1). Normal loading pressure F_N is assumed as fixed, and $a + b\varphi_4(S_m) = a'$. Thus, formula (2) is changed into:

$$\ln \eta_{ijk} = a' + b\varphi_1(S_i^1) + c\varphi_2(S_j^2) + d\varphi_3\left(S_k^3\right) \qquad (9)$$

Because $b = 4546$ is already known owing to undetermined constants a' and d, temperature has no interaction with velocity and pressure. Therefore, when the values of a' and d are estimated at temperature stress of 338K, term $b\varphi_1\left(S_i^1\right)$ becomes a constant, and formula (9) is transformed into twin-stress parameter estimation.

Let $a' + b\varphi_1(S_i^1) = g$, and presume that velocity interacts with pressure. Formula (15) is changed into:

$$\ln \eta_{ijk} = g + c\varphi_2(S_j) + d\varphi_3\left(S_k\right) + h\varphi_{23}\left(S_j, S_k\right) \qquad (10)$$

$$\ln \eta_{ijk} = g + c\varphi_2(S_j) + d\varphi_3\left(S_k\right) + h\varphi_{23}\left(S_j, S_k\right) \qquad (11)$$

Where the last term represents the interaction between velocity and pressure.

Let

$$\varphi_j = \varphi_2(S_j), \varphi_k = \varphi_3(S_k) \qquad Var\left(\hat{\delta}_{jk}\right) = \zeta\left(2, r_{jk} - 1\right)$$

r_{jk} is the censored data of life test with fixed failure number of number n_{jk} of samples placed under horizontal combination (j, k), ζ_{jk} is the Riemann ζ function, and $\hat{\delta}_{jk}$ is the unbiased estimator of $\ln\eta_{ijk}$ [8 and 9].

$\hat{\delta}_{jk}$ is the unbiased estimator of $ln\eta_{ijk}$ [8 and 9].

$$\Delta = \begin{pmatrix} \hat{\delta}_{11} \\ \hat{\delta}_{12} \\ \vdots \\ \hat{\delta}_{jm} \\ \vdots \\ \hat{\delta}_{jk} \\ \vdots \\ \delta_{lk} \end{pmatrix}, A = \begin{pmatrix} 1 & \varphi_1^2 & \varphi_1^3 & \varphi_{11} \\ 1 & \varphi_1^2 & \varphi_2^3 & \varphi_{12} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \varphi_1^2 & \varphi_k^3 & \varphi_{1k} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \varphi_j^2 & \varphi_k^3 & \varphi_{jk} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \varphi_l^1 & \varphi k & \varphi_{lk} \end{pmatrix}, \alpha = \begin{pmatrix} g \\ c \\ d \\ h \end{pmatrix} V^* = diag\left(\zeta_{11}\zeta_{12}\cdots\zeta_{1k}\cdots\zeta_{lk}\right) \qquad (11)$$

Its matrix form is:

$$\begin{cases} E(\Delta) = A\alpha \\ Var(\Delta) = V^* \end{cases} \qquad (12)$$

With Gauss-Markov transformation being performed on the above formula, estimated parameter α in the acceleration model can be obtained:

$$\hat{\alpha} = \left(A'V^{*-1}A\right)^{-1} A'V^{*-1}\Delta \qquad (13)$$

Where A' represents the transposed matrix of A, and V^{*-1} represents the inverse matrix of matrix V^*. The variance-covariance matrix of $\hat{\alpha}$ is:

$$Var\ (\hat{\alpha}) = \left(A'V^{*-1}A\right)^{-1} \qquad (14)$$

Suppose the calculated inverse matrix is:

$$\left(A'V^{*-1}A\right)^{-1} = D = \left(D_{jk}\right)$$

Then holds: $Var\ (\hat{\alpha}) = D_{jj},\ j = 0,1,2,3$

$$Cov\left(\hat{\alpha}_j, \hat{\alpha}_k\right) = D_{ijk}, k = 0,1,2,3$$

Then $\hat{\alpha}$ can be expressed as:

$$\begin{cases} g = \sum_j \sum_k \zeta_{jk}^{-1} \delta_{jk} \left(D_{00} + D_{01}\varphi_j^2 + D_{02}\varphi_k^3 + D_{03}\varphi_{jk} \right) \\ c = \sum_j \sum_k \zeta_{jk}^{-1} \delta_{jk} \left(D_{10} + D_{11}\varphi_j^2 + D_{12}\varphi_k^3 + D_{13}\varphi_{jk} \right) \\ d = \sum_j \sum_k \zeta_{jk}^{-1} \delta_{jk} \left(D_{20} + D_{21}\varphi_j^2 + D_{22}\varphi_k^3 + D_{23}\varphi_{jk} \right) \\ h = \sum_j \sum_k \zeta_{jk}^{-1} \delta_{jk} \left(D_{30} + D_{31}\varphi_j^2 + D_{32}\varphi_k^3 + D_{33}\varphi_{jk} \right) \end{cases} \tag{15}$$

With test stress spectra and related data in Table 3 being substituted into formula (15), unbiased estimators of the parameters can be obtained according to formulas (11), (13), (14) and (15).

$$\Delta = \begin{pmatrix} 6023 \\ 422 \\ 316 \\ 203 \end{pmatrix}, A = \begin{pmatrix} 1 & ln1.1 & 0.2 & 0.2/ln1.1 \\ 1 & ln1.19 & 0.3 & 0.3/ln1.19 \\ 1 & ln1.27 & 0.5 & 0.5/ln1.27 \\ 1 & ln1.40 & 0.7 & 0.7/ln1.40 \end{pmatrix} \qquad \hat{\alpha} = \begin{pmatrix} g \\ c \\ d \\ h \end{pmatrix} = \begin{pmatrix} 15.35 \\ -0.445 \\ -1.47 \\ 0.057 \end{pmatrix}$$

According presumed examination, the last term in formula (16) is very small, i.e., the temperature-velocity interaction term has little influence on $\ln \eta_{ijk}$. Therefore, this term should be removed in the first place. Thus, the acceleration model is changed into:

$$\ln \eta_{ijk} = g + c\varphi_2(S_j) + d\varphi_3(S_k)$$

With α being estimated once more, the following formula is obtained:

$$\alpha = \begin{pmatrix} g \\ c \\ d \end{pmatrix} = \begin{pmatrix} 16.365 \\ -0.73 \\ -1.08 \end{pmatrix} \qquad Var(\hat{\alpha}) = \begin{pmatrix} 1.45 & -2.32 & -1.05 \\ & 1.107 & 1.14 \\ & & 0.99 \end{pmatrix}$$

The variance-covariance matrix of α is:

$$Var = \begin{pmatrix} 5340 & -1232\times10^4 & 663 & 23\times10^3 \\ & 6435\times10^4 & 23\times10^4 & -105\times10^4 \\ & & 189 & -3.2\times10^4 \\ \text{symmetric part} & & & 1533\times10^4 \end{pmatrix}$$

Where $\hat{c} = -0.73$, which accords with the result of twin-stress accelerated life test with temperature and velocity as acceleration stress. With $\hat{b} = 4546$ and $T = 338K$ being substituted in $a + b\varphi_1(S_i) = g$, a' is solved as 2.90.

Thus, the life-stress model is determined:

$$ln\ \theta_{ijk} = 2.90 + 4546/T_i - 0.73\ ln\left(1 + V_j\right) - 1.08\ P_k \tag{16}$$

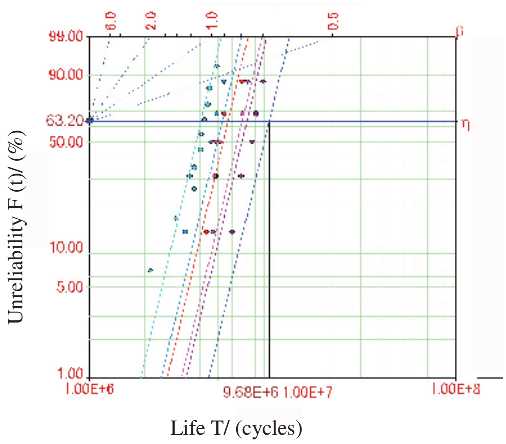
5.2. Life calculation at temperature of 338K and at normal velocity and pressure level

With temperature being fixed at 338K, characteristic life at normal velocity and pressure stress is calculated. The calculation can refer to the theory of twin-stress accelerated life test for cylinders, and corresponding test can be performed for comparison. The experimental results are compared with calculated values, as shown in Table 5:

Table 5 Stat. of characteristic life at 338K and at normal velocity and pressure

comparison item	$\hat{\eta}$ (cycles)	*MTTF/ (cycles)*	variance $\hat{\sigma}_T$
Life value of experiments under normal stress	9654000	9042000	336100
Life value of calculation by acceleration model at normal stress	9677262	9054331	214200
Error	0.24%	0.13%	

Table 5 shows that the difference of the characteristic life calculated based on the mathematical model with that obtained from test is 2.1%, within the allowed range. Therefore, the model is valid. The five groups of experimental data are integrated with calculation results, and the general Weibull distribution is shown in Fig. 3:



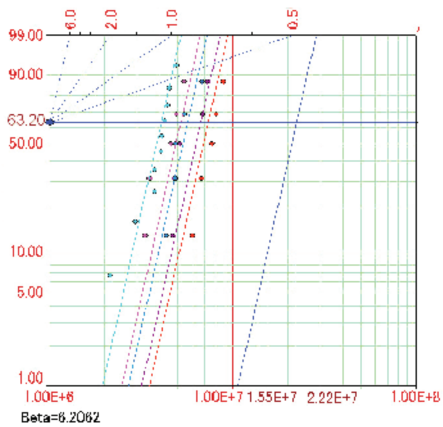


Fig. 3 Stat. of characteristic life at normal velocity & pressure

Fig. 4 Stat. of calculated life and test life at normal stress

5.3. Life calculation at normal temperature, velocity and pressure

Various life indications at normal temperature, pressure and velocity are calculated according to formula (10), as shown in Table 6:

Table 6 Estimation of life characteristic under normal stress

comparison item	$\hat{\eta}$ (cycles)	*MTTF/ (cycles)*	variance $\hat{\sigma}_T$
Life value of experiments under normal stress	18130000	16780000	334200
Life value of calculation by acceleration model at normal stress	17080000	16010000	334300
Error	0.49%	0.53%	0.03%

With the five groups of test data being integrated with calculated results obtained at normal stress, the Weibull distribution is shown in Fig. 4.

5.4. Analysis of Stat. results

According to the curve of acceleration factor vs. stress, the stress of velocity and pressure accelerates the life test to different degrees;

From Table 5, Table 6, Fig. 3 and Fig. 4, it can be deduced that the differences of two couples of test values and calculated values are both less than 5%, which is within the allowed range, indicating that acceleration model (1) and estimation of model parameters are correct; such a result also proved that the optimization scheme combination is effective, and its test results can reproduce various life indications at normal stress.

Acknowledgements

The data from triple-stress accelerated life test reproduced cylinder's life indications at normal stress level precisely.

The acceleration model described in formula (1) presents the function relation of various variables with life as well as their measurement units definitely. It is the development and supplement of Arrhenuis model and Eyring model;

Temperature, velocity and pressure accelerate test process to different degrees. Accelerated life test was performed on cylinders under the three acceleration stress types, and the test period was further shortened in comparison with twin-stress test.

References

[1] Liu Jiajun. Material wear principle and wear resistance [M]. Beijing: Tsinghua University Press, 1993: 2-167

[2] Yao Lizhen. Reliability Physics [M]. Beijing: Electronic Industry Press, 2004: 33-34

[3] Jiang Renyan and Zuo Mingjian. Reliability model and application. Beijing: China Machine Press, 1999: 228-334

[4] Mao Shisong and Wang Lingling. Accelerated life test [M]. Beijing: Science Press, 2000. 85

[5] Jia Jitao. Accelerated life test for pneumatic products [D]. Beijing: Beijing University of Aeronautics and Astronautics, 2004: 1-78

[6] Zhang Zhihua. Accelerated life test and Stat. analysis [M]. Beijing: Press of Beijing Polytechnic University, 2002, 218.

[7] Chen Juan. Accelerated life test method for pneumatic products [post-doctoral dissertation]. Beijing: Beijing University of Aeronautics and Astronautics, 2005.

[8] Escobar L A, Meeker W Q.Fisher information matrix for the extreme value normal and logistic distribution and censored data [J]. Applied Statistics, 1994, 43(3):533-540.

[9]Escobar L A, Meeker W Q.Planning accelerated life tests with two or more experimental factors [J]. Techmometrics, 1995, 37(4):411-427.